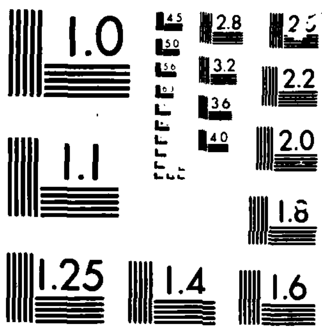
AD-A167 032 CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION(U) ARIZONA UNIV TUCSON ENGINEERING EXPERIMENT STATION D M MCELIGOT 29 NOV 85 1248-11 N00014-75-C-0694 1/1

UNCLASSIFIED F/G 20/13 NL



MICROCOPY CHART

(12)

FINAL REPORT

Contract N00014-75-C-0694; NR-097-395

CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION

Donald M. McEligot
Aerospace and Mechanical
Engineering Department

29 November 1985

Final report for period:
1 April 1974 - 30 September 1985

Prepared for:

OFFICE OF NAVAL RESEARCH
Code 1132p
800 N. Quincy Street
Arlington, Virginia 22217

FINAL REPORT

Contract No. N00014-75-C-0694; NR-097-395

CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION

Donald M. McEligot
Aerospace and Mechanical Engineering Department
University of Arizona
Tucson, Arizona 85721

29 November 1985

Final report for period:
1 April 1974 - 30 September 1985

Prepared for:

OFFICE OF NAVAL RESEARCH
Code 1132p
800 N. Quincy Street
Arlington, VA 22217

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited; reproduction in whole or in part is permitted for any purpose of the U.S.Govt.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): 1248-11

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Engineering Experiment Station, College of Engineering

6b. OFFICE SYMBOL (If applicable):

6c. ADDRESS (City, State and ZIP Code): University of Arizona, Tucson, Arizona 85721

7a. NAME OF MONITORING ORGANIZATION: Office of Naval Research, Bandolier Hall West - Room 204

7b. ADDRESS (City, State and ZIP Code): University of New Mexico, Albuquerque, New Mexico 87131

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Office of Naval Research

8b. OFFICE SYMBOL (If applicable):

8c. ADDRESS (City, State and ZIP Code): Code 1132p, 800 N. Quincy Street, Arlington, Virginia 22217

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
NR-097-395			

11. TITLE (Include Security Classification): CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION (U)

12. PERSONAL AUTHOR(S): McEligot, Donald M., P. O. Box 4282, Middletown, Rhode Island 02840

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 4/1/74 TO 9/30/85

14. DATE OF REPORT (Yr., Mo., Day): 29 November 1985

15. PAGE COUNT: 38

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Heat transfer, Pulsating flow, Turbulent flow, Tubes, Boundary layers, Gas turbine systems, Forced convection, Heat Exchangers, Laminar flow, Augmentation, Enhancement, Brayton cycle, Dissociating gases, Rough walls, Complex flows

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

For application to gas turbine cycle and Rankine cycles in Naval propulsion, measurements and analyses have been conducted of the following topics: heat transfer to mixtures of gases; heat transfer to pulsating, turbulent gas flow, dissociating gas power cycles; heat transfer at a smooth-to-rough transition; numerical prediction of flow and heat transfer from ribbed surfaces; turbulent heat transfer in a swirl flow downstream of an abrupt pipe expansion and heated, laminarizing gas flows.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: M. K. Ellingsworth

22b. TELEPHONE NUMBER (Include Area Code): (202) 696-4403

22c. OFFICE SYMBOL: ONR 1132p

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified

TABLE OF CONTENTS

SUMMARY

Background

Current naval propulsion plants are powered by variations of the Rankine cycle (steam) or the open gas turbine cycle (air and combustion products), plus some diesel engines in small ships. Alternative power systems suggested include the closed gas turbine cycle and cycles involving dissociation of the working fluid in either a Rankine or a gas cycle. These latter two are believed to offer the potential of substantial improvement in the power-to-weight ratio of the propulsion plant. The studies conducted considered basic problems in convective heat transfer and flow friction that are important in all of the above.

Convective heat transfer provides the dominant thermal resistance in several components of conventional steam power plants, as well as in all heat transfer components in gaseous cycles. For example, the overall thermal resistance from the condensing steam to the cooling water in the main condenser of a naval ship is dominated by the convective thermal resistance of the cooling water inside the tubes [Marto and Nunn, 1980]. One can expect significant reductions in tube length and, therefore, size and weight of the condenser and overall plant if the convective heat transfer coefficient of the cooling water side is increased appreciably. Likewise in the superheater of a conventional naval steam generator, calculations for typical conditions show that the dominant resistance is the forced convection on the outside of the tubes and, of the two modes, convection is more important than radiation [Harrington, 1971]. The flow in this case is complicated since the Reynolds number is relatively low and--due to the large temperature difference--the gas properties vary through the boundary layer by a factor of two. Again, improvement in this convective heat transfer and its prediction can provide reductions in size and weight of the unit.

The convective heat transfer coefficient can be improved by disrupting the smooth surface by adding various roughness elements which cause increased mixing in the viscous layer (so-called laminar sublayer and buffer layer) [Bergles, 1978]. It has also been suggested that vigorous mixing, induced by artificially roughened surfaces, can also combat fouling in sea water flows through marine condensers. In the case of a gas, dissociation leads to higher heat transfer coefficients. Since the optimization of dissociating gas power plants depends on the recombination of the fluid in a regenerative heat exchanger or a cooler, roughening the surface has also been suggested as a means of improving the recombination rate, as well as enhancing the reduced heat transfer coefficients.

In order to assess the benefits of roughness elements on the inside of condenser tubes or outside of superheater tubes or other components, in inhibiting fouling and in enhancing recombination in dissociated gases, it is necessary to develop reliable prediction methods for computing the flow field, heat and mass transfer rates and chemical reaction rates to compare proposed rough surfaces to smooth surfaces.

The advantages of adding a low molecular weight gas to one of high molecular weight, to provide a gas mixture with low Prandtl number, in a closed gas turbine (Brayton) cycle can include potential optimization of the heat exchange equipment and turbo-machinery, improvement of heat transfer properties, reduction of impurities and elimination of combustion products which can contaminate blades and surfaces. But it is also of interest to note that the University of Dayton Research Institute is develop-ing a Rankine cycle engine utilizing the mixing of a gas of light molecular weight with a heavy fluid [Mech. Eng., Dec. 1979] in order to improve efficiency and increase operating life.

In a study of potential working fluids for power cycles, McKisson [1954] pointed out the advantages of utilizing the endothermic nature of some dissociation reactions to increase the energy absorbing capacity of the fluid. Pressler [1966] and Callaghan and Mason [1964] and others have shown in early measurements that the convective heat transfer coefficient may be improved as well. For use in a power cycle the dissociated fluid must recombine in another component, typically in a regenerative heat exchanger, cooler or condenser. Thus heat transfer with both dissociation and recombining fluids is of importance. Our Professor Perkins [Serksnis et al., 1978] has noted the benefits of using the dissociating fluid in the turbine. Bazhin et al., [1970] have examined gas and gas-liquid cycles using dissociating working media to determine the effect of parameters on power plant efficiency, particularly for fast nuclear reactors; N_2O_4, Al_2Cl_5 and Al_2Br_6 received primary interest.

Haynes [1970] reports the following advantages of dissociating power cycles:

1. Compared to steam turbines, the N_2O_4 cycle requires 4 to 5 times less metal investment,
2. At 520-540°C and 130-170 atmospheres, the efficiency of the N_2O_4 cycle is greater than similar cycles of CO_2, H_2O, He and others, and
3. Analyses carried out show the possibility of a substantial improvement (by 20-30%) in the technical-economic indices of fast gas cooled reactors using N_2O_4 compared with atomic electric stations using sodium.

The potential benefits for ship propulsion are obvious. However, with the emphasis to date concentrating on improved efficiency, it is now necessary to examine the thermodynamic cycles to deduce the ranges of operating parameters which lead to optimization of the power-to-weight ratio in naval ships.

A common geometry recurring in compact naval propulsion plants is a change in duct size in the primary fluid loop. As a consequence of the upstream plumbing, the fluid is often swirling about the axis in the piping. Heat losses from the primary fluid and thermal stresses in the component depend on the convective heat transfer from the fluid to the component as it undergoes this geometrical transition. The idealized problem is a study of heat transfer in a sudden expansion with swirl flow. The numerical analyses employed in examining the detailed flow about roughness elements have features in common with this problem, so it has also been studied as an extension of previous work.

Heat Transfer to Mixtures of Gases

In addition to other applications, mixtures of inert gases can be used to improve performance in closed gas turbine cycles. In our early work, heat transfer and wall friction parameters were obtained numerically to demonstrate the effects of mixture composition and gas property variation for heating or cooling in regenerative heat exchangers of such cycles; the situation was modeled by laminar flow through short ducts with constant wall heat flux [McEligot, Taylor and Durst, 1977]. For design predictions accounting for the effect of property variation, it was found that the property ratio method is better than the film temperature method for heat transfer, while the latter method is preferrable for apparent wall friction--with the proviso that specific definitions of the nondimensional parameters be employed.

Numerical predictions for turbulent flow in circular tubes at low heating rates showed that accepted empirical correlations might overpredict heat transfer coefficients significantly for helium-xenon mixtures. However, the numerical predictions themselves were found to be strongly dependent on the choice among turbulence models which have been hypothesized by various authors.

For comparison to the predictions and correlations, measurements of heat transfer and pressure drop were obtained in a smooth, electrically heated, vertical circular tube with air, helium, a helium-argon mixture and a hydrogen-carbon dioxide mixture with molecular weights ranging from 14.5 to 29.7 for temperatures from about 75° to 1040°F and Reynolds numbers of 8000 to 125,000 [McEligot, Pickett and Taylor, 1976; Serksnis, Taylor and McEligot, 1978; Pickett, Taylor and McEligot, 1979]. The Prandtl number was varied from 0.34 to 0.7 by varying the mixture composition. Popular existing experimental correlations, developed using gases with Prandtl numbers of the order of 0.7, were found to overpredict the observed Nusselt numbers, thereby confirming our earlier numerical predictions. By comparison of numerical calculations and measured constant property Nusselt numbers, turbulent Prandtl numbers were determined in the wall region. For the range of Prandtl numbers examined it was found that $Pr_{t,wall} = 1.0 \pm 0.1$. The validity of using these deduced turbulent Prandtl numbers was also confirmed for conditions where the properties vary significantly.

In order to conduct measurements at lower Prandtl numbers, the apparatus was modified to a closed loop configuration to contain expensive mixtures of xenon with helium or hydrogen. Initial experiments using a commercial gas booster pump for circulating the gas showed a substantial reduction of mean heat transfer parameters when the pulsations were superposed on the main flow. By adding plenum chambers and more pressure regulators, the percent oscillation was reduced to near steady flow. Experiments in the modified apparatus extended the Prandtl number range down to 0.16 with a hydrogen-xenon mixture.

At a Prandtl number of about 0.2, the predictions of accepted correlations for heat transfer in fully established tube flow differ by a factor more than two. By mixing helium with xenon, or hydrogen with xenon, the range $0.16 \lesssim Pr \lesssim 0.7$ can be obtained. Measurements with these mixtures in a vertical tube showed that the Colburn analogy and Dittus-Boelter correlation substantially overpredict the Nusselt number for constant property conditions; best agreement was provided by relations suggested by Petukhov and by Kays, as in Figure 1 [Taylor, Bauer and McEligot, 1984, 1985]. For moderate variation of gas properties ($1 \lesssim T_w/T_b \lesssim 2.2$) the correlation for average friction factor by Taylor was verified; the exponent on the Prandtl number

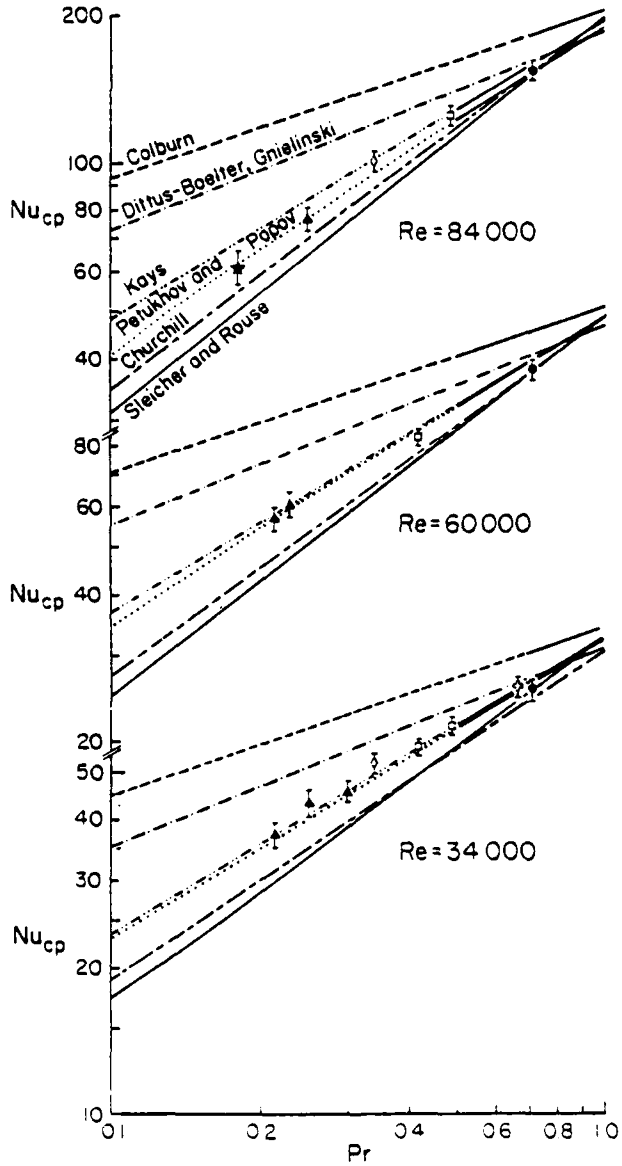


Figure 1. Measured Nusselt number compared to predictions from correlations proposed by other investigators for constant properties [Taylor, Bauer and McEligot, 1985].

in his equation for heat transfer was modified to 0.65 to accommodate these new data.

Heat Transfer to Pulsating, Turbulent Gas Flow [Park, Taylor and McEligot, 1982a,b]

Heat transfer to pulsating flow occurs frequently in practice; one example is in flow systems with reciprocating compressors. However, recent theoretical and experimental investigations of heat transfer to fluids in pulsating flow have led to numerous contradictions.

The major objective of the experiment was to investigate the effects of flow pulsations on heat transfer in the thermal entry region for turbulent gas flow at a moderate Reynolds number in a circular tube. Local heat transfer measurements for pulsating flows were compared to those with steady flow at the same conditions in a smooth, electrically heated, vertical tube. Pulsations were generated by a reciprocating gas compressor which was located upstream of the measuring test section.

Mass flow rates were calculated from measurements with positive displacement meters at the exit of the flow section after cooling and throttling. Simultaneous recordings of pressure and pressure drop were obtained at locations between the test section and the reciprocating pump to measure the wave form of the pulsation. The accuracy of the data was confirmed by tests in turbulent flow without pulsations, but this study concentrated on direct comparisons between the two situations.

Inlet Reynolds numbers varied from 19,000 to 102,000; Mach numbers were 0.15 or below; pulsation frequencies ranged from 2.1 to 3.6 Hz and the peak-to-peak pressure fluctuations varied from 9 to 29 percent of the mean pressure. At these conditions the nondimensional frequency $\alpha = \sqrt{2\pi f/\nu}$, varied from about 4 to 7-1/2; in laminar flow, quasi-steady approximations become weak when this frequency becomes greater than about two, but for turbulent heat transfer in this Reynolds number range the limitations are still to be determined.

Direct comparison showed all pulsating data to agree with the corresponding values for steady flow within 7-1/2 percent. For Re $\gtrsim 5 \times 10^4$ the pulsating measurements essentially confirmed quasi-steady analyses, which predict a slight reduction in heat transfer parameters, within the reproducibility of the experiment. At lower Reynolds numbers the reduction was larger and increased as α was increased.

Dissociating Gas Power Cycles

Power cycles using gases which dissociate at relatively low temperatures, such as N_2O_4, have been recommended for large central station power plants [Krasin, 1970]. The main advantages have been mentioned in the preceding summary. To date most interest has concentrated on prediction of the thermal efficiency of the plant. We considered application to shipboard power plants and examined effects on the power-to-weight ratio of a potential plant [Postan, 1982]. The objective of these studies was to determine the approximate operating parameters of a naval propulsion plant using the cycle, so that basic research on convective heat transfer to dissociating/recombining gases could be directed towards the appropriate ranges.

Thermodynamic data for the chemically-reacting nitrogen tetroxide system in chemical equilibrium were fitted to simple relations. These relations were used to provide approximate estimates of the power-to-weight ratio, network output per unit mass of fluid flowing and thermal efficiency of a gas power plant using an idealized representation of N_2O_4 as the working medium. Compared with predictions for air as the working fluid, the results indicated larger power-to-weight ratios and larger specific net work for pressure ratios from 0 to 60 and turbine inlet temperatures from 850 to 1200K. Preliminary predictions showed the weight of components could be reduced to the order of one-half to one-third by using dissociating N_2O_4.

<u>Heat Transfer at a Smooth-to-Rough Transition</u>

Convective heat transfer in turbulent flow can be enhanced by disrupting the viscous sublayer to cause increased turbulent mixing in the boundary layer. The viscous sublayer disruption can be accomplished by surface roughness element of various geometries and patterns. Although past experiments have shown that rectangular rib elements can enhance heat transfer parameters by a factor of two or three, there are currently no suitable means of predicting such enhancement without experimentation. Further, the effects of property variation coupled with the roughness elements are not well known.

For a number of applications enhancement is only necessary locally along the flow channel; therefore, the experiment examined the transition from a smooth, heated surface to a rough one [McCullough, 1985]. A rough surface of transverse rectangular ribs was studied. Air passed through a rectangular duct with an aspect ratio greater than 12 and, therefore, was idealized as two-dimensional flow between flat plates. Flow was asymmetric since only one plate had roughness elements and heating. The duct consisted of an adiabatic smooth section of 36s) in length (s = spacing) for flow development, followed by a heated section of 12s constructed from smooth plate, 12s with roughness elements, and a final 12s of smooth plate. The test apparatus was designed for optimal rib height, $h^+ \approx 20$, at a Reynolds number of 20,000. The apparatus was also built for a maximum wall-to-inlet temperature ratio of four to examine effects of air property variation.

Measurements for a Reynolds number range of 10,000 to 20,000 have been conducted. The data were used to evaluate the local Nusselt number as a function of heating rate and Reynolds number. These experimental results are compared to numerical predictions based on the program of Schade and McEligot [1971], which uses a van Driest turbulence model and turbulent Prandtl number to model the boundary layer in the smooth sections of the duct, in Figure 2. In the rough section, the van Driest mixing length model is no longer appropriate near the wall, so a mixing length model using a roughness Reynolds number, Re_k, is used.

The data clearly indicated an increase in Nusselt number resulting from the roughness elements, as expected. Temperature profiles along the test surface showed a reduction in the rate of temperature increase or, for the higher Reynolds number runs, a decline in temperature through the rough section. This observation demonstrates an improved heat transfer coefficient in the rough area over the smooth area. The effect was more pronounced at the upper end of the Reynolds number range. In the vicinity of the smooth-to-rough transition, augmentation of heat transfer parameters was moderated by streamwise conduction in the test plate.

<u>Numerical Prediction of Flow and Heat Transfer from Ribbed Surfaces</u> [Faas and McEligot, 1980]

Currently, development of optimal rough surfaces for a given application is a time-consuming process requiring extensive experiments. In order to reduce the number of experiments required, we developed numerical prediction methods by extending an existing program for two-dimensional recirculating flows, "TEACH" [Gosman and Ideriah, 1976].

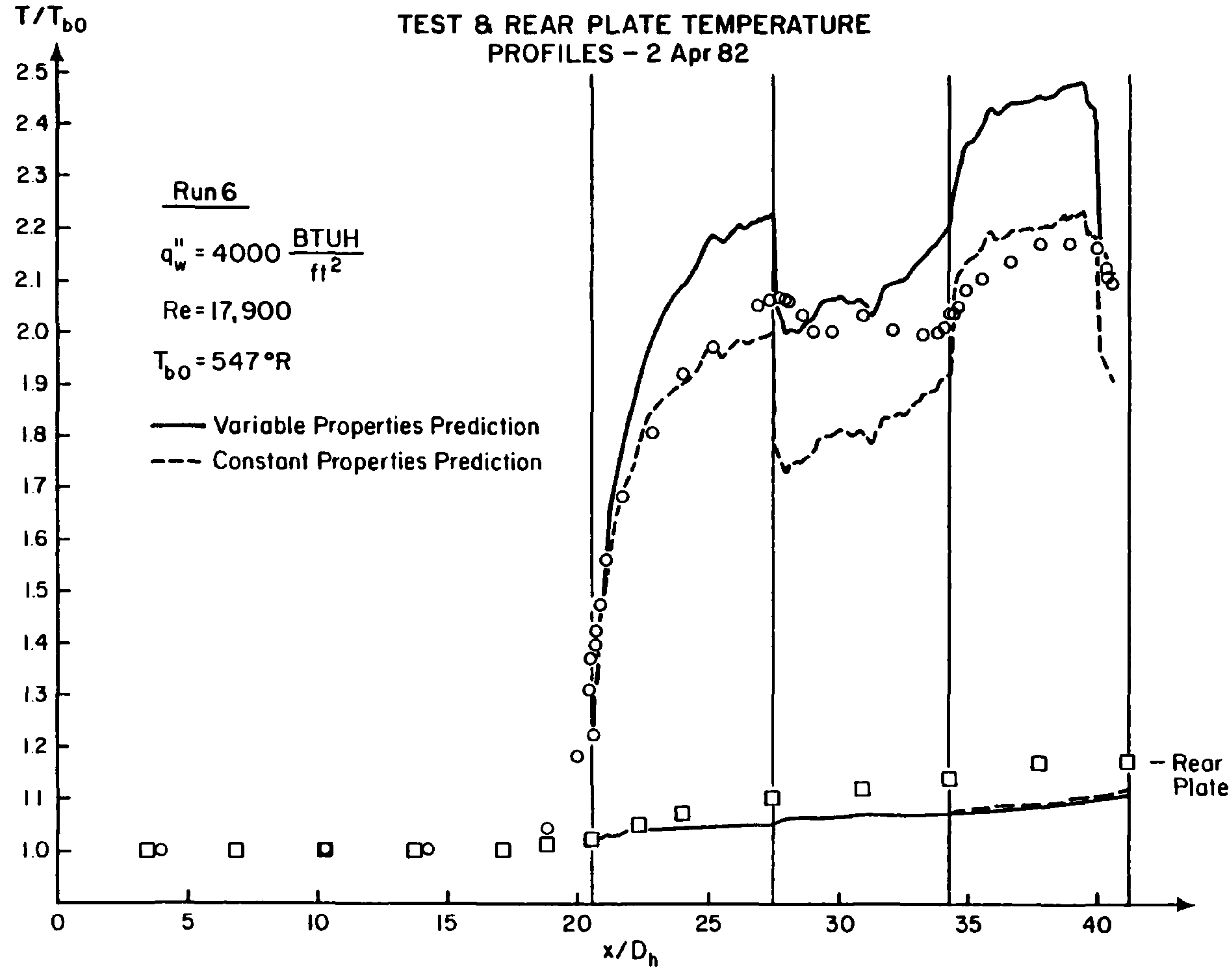


Figure 2. Measurements of heat transfer at smooth/rough/smooth transition [McCullough, 1985].

Short [1978] modified the "TEACH" program to treat flow around a rectangular rib with periodic boundary conditions consistent with the spatially periodic disturbance of the flow by the ribs. His preliminary study was confined to laminar flow but considered dimensions of the same order as would be appropriate for turbulent flow to test scaling difficulties.

Since applications to practical power cycles will likely require materials such as stainless steel--which has a low thermal conductivity--and the flow conditions plus roughness geometry will be chosen for improved convective heat transfer, the thermal resistance in the solid wall may approach that of fluid. Consequently, the general problem is one of coupled convection and conduction. To accommodate both resistances, Short extended the numerical method to solve the energy equation in both the fluid and the wall, simultaneously.

Short's flow results appear good and his thermal results show the correct trends. The locations of the maximum and minimum wall temperatures, as well as the maximum and minimum heat transfer coefficients, are reasonable and agree with published data and calculations.

Faas [1979] extended the study of Short; two geometries were treated: flow in a corrugated duct, as for a plate-fin heat exchanger, and flow over surfaces with repeated ribs to improve heat transfer to gases. Initial attempts to impose the boundary conditions by a version of a generalized Newton-Raphson method were unsuccessful, but a more direct iterative technique, referred to as the "internal plane method," worked well. Essentially, the numerical grid covers two unit cells and trial boundary conditions are held constant until the iterative solution approaches convergence. The solution at an internal plane, which is either identical to the boundaries or an image plane, is then applied as the next estimate of the boundary values and the procedure is repeated.

For flow over repeated ribs in a two-dimensional duct, predictions were made at Re = 400 and Pr = 0.7 including treatment of the thermal conduction problem in the plate. Dimensions corresponded to the design of our rough wall test section with air taken as the fluid and stainless steel as the wall material. Average results were Nu = 8.45 and f = 0.70 compared to 8.24 and 0.060, respectively, for a smooth wall. Other results are presented in an earlier annual report [Faas and McEligot, 1980].

Turbulent Heat Transfer in a Swirl Flow Downstream of an Abrupt Pipe Expansion
[Habib and McEligot, 1981, 1982]

The problem of improving the heat transfer in circular ducts is of great importance in the engineering field; its application is found, for example, in heat exchangers and combustion systems. Two cases in which heat transfer is augmented are swirling flows and flows downstream of a sudden pipe expansion. In both cases, separation and swirl cause high shearing rates which are associated with 1) high rates of generation of turbulence kinetic energy and 2) increase in the length scales which lead to a reduction in the rate of dissipation of turbulence kinetic energy. All these features reduce the viscous sublayer through which heat must pass largely by molecular diffusion. These two cases have been rarely studied numerically. The combined effect of swirl and abrupt enlargement on heat transfer parameters apparently had not been studied before our investigation.

Our study developed numerical predictions of flow and heat transfer downstream of a sudden expansion applied to turbulent swirl flow in a pipe. The calculations were obtained by the numerical solution of the time-averaged forms of the continuity, momentum and thermal energy equations together with transport equations for the kinetic energy of turbulence and its rate of dissipation. The effect of body forces due to streamline curvature on turbulence was taken into consideration by specifying one of the empirical constants in the dissipation equation as a function of the flux Richardson number [Bradshaw, 1973].

For the case of a sudden expansion without swirl, prediction for the experiment of Zemanick and Dougall [1970] produced satisfactory agreement with measured local Nusselt numbers. For the swirling case there were no data available for comparison; however, the measurements of Beltagui and

MacCullum [1976] for a sudden expansion with swirl, but without heat transfer, were used to obtain confidence in the results of the flow field calculations.

The calculations encompassed the effects of swirl and Prandtl number on heat transfer parameters for swirl flow down-stream of an abrupt pipe expansion, with a constant wall temperature as the thermal boundary condition. They were made for ranges of swirl number from 0.0 to 1.0 and of Prandtl number of 0.7 (air) to 10 (water). The effects of the swirl number on the velocity and temperature fields were also determined. The results predicted that as the swirl number increases, the Nusselt number will increase near the expansion and the position of its maximum value will move towards the inlet section. At downstream locations and low swirl numbers, the Nusselt number appeared to decrease slightly with an increase in the swirl number. The results also suggested that increasing the Prandtl number will increase the local Nusselt number.

Heated, Laminarizing Gas Flows

Measurements of mean velocity and mean temperature fields and wall parameters for air flowing in a smooth, vertical tube at low entry Reynolds numbers were obtained for heating with constant wall heat flux along the heated length [Shehata, 1984]. Two entry Reynolds numbers of approximately 6,000 and 4,000 were employed with three heating rates, $q^+ = q_w/(Gc_{p,i}T_i)$, of 0.0018, 0.0035 and 0.0045 approximately. The flow development was measured by obtaining internal profiles along the heated length at axial locations from 3.2 to 24.5 diameters. An adiabatic entry of 50 diameters preceded the heated region. The three heating rates caused slight, large and severe property variation of the air. The highest heating rate was found to cause significant buoyancy effects.

The internal measurements were obtained using constant temperature hot-wire anemometry and resistance thermometry for velocity and temperature, respectively, employing a single short wire probe. A technique was developed and employed for the use of a single short hot wire in velocity measurements in non-isothermal flows.

The measurements were compared to numerical predictions employing two simple versions of the van Driest mixing length turbulence model, Figure 3. In general, both models agreed with the measurements reasonably well, but for the higher heating rates neither model was completely satisfactory in predicting the velocity profiles. When the buoyancy parameter reached 0.3, the peak velocity occurred in the wall region rather than at the tube centerline. Typically, the Nusselt number was overpredicted by 10% for $x/D > 14$ and, consequently, the wall temperature was underpredicted by about 7%.

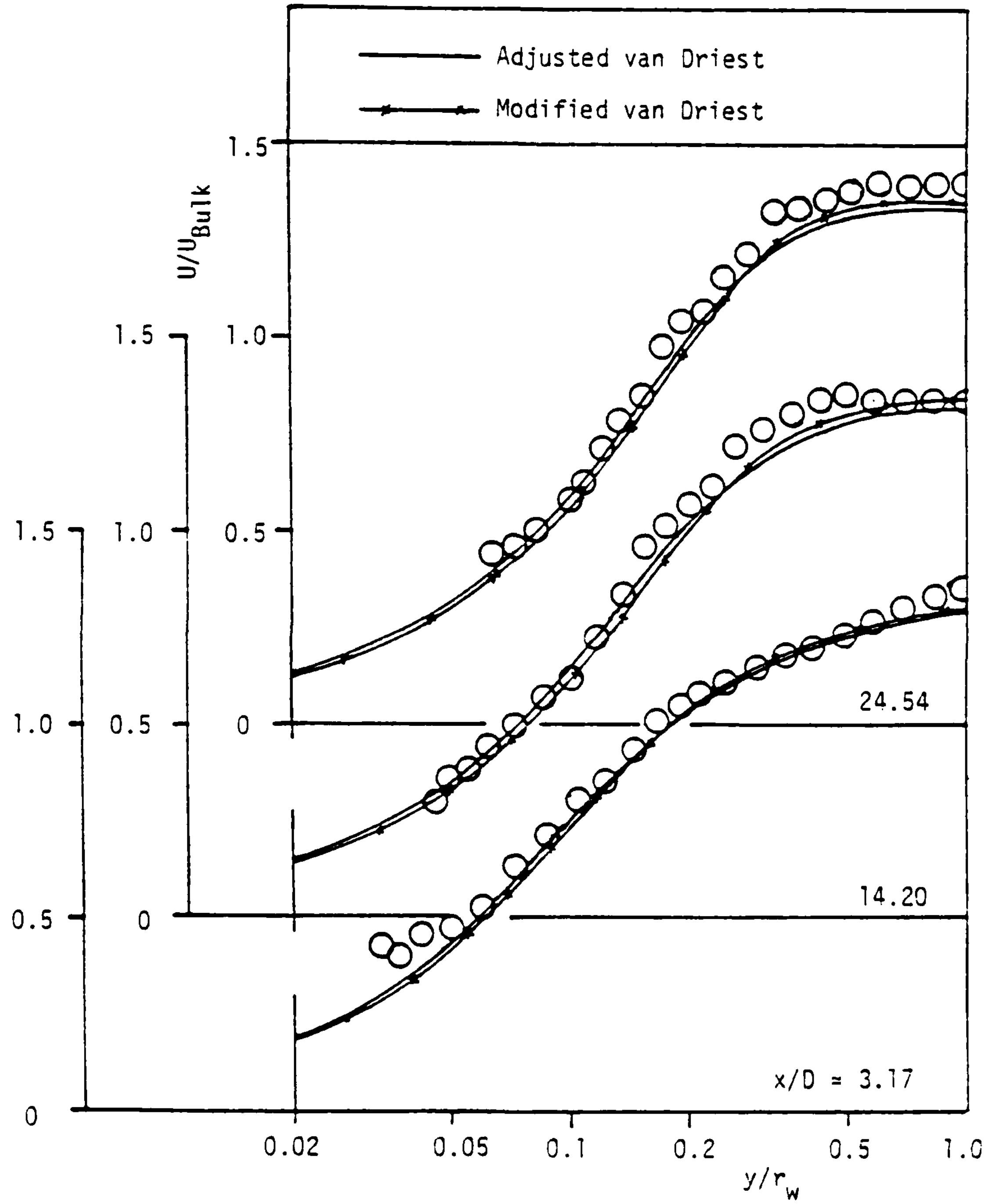


Figure 3. Axial momentum development presented in stretched coordinates. $Re_i \simeq 4{,}000$; $q^+ \simeq 0.0045$ [Shehata, 1984].

References Cited

Bankston, C. A. and D. M. McEligot, 1970. Turbulent and laminar heat transfer to gases with varying properties in the entry region of circular ducts, Int. J. Heat Mass Transfer, 13, 319-344.

Bazhin, M. A., V. P. Bubnov, V. B. Nesterenko and N. M. Shiryayeva, 1970. Optimizing the parameters of power plants using dissociating working media. Rept. FTD-MT-24-1924-71, SP-AFB.

Beltagui, S. A. and N. R. L. MacCullum, 1976. Aerodynamics of vane-swirled flames in furnaces, J. Inst. Fuel, 49, p. 183.

Bergles, A. E., 1978. Enhancement of heat transfer, Heat Transfer 1978 (Sixth Int. Heat Transfer Conf., Toronto), 6, 89-108.

Bradshaw, P., 1973. Effects of streamline curvature on turbulent flow. AGARDograph 169.

Callaghan, M. J. and D. M. Mason, 1964. Momentum and heat transfer correlations for a reacting gas in turbulent pipe flow. AiChE J, 10, 52-55.

Faas, S. E., 1979. Numerical prediction of flows in two-dimensional ducts with repeating surface geometries. M.S.E. Report, Aero. Mech. Engr., Univ. of Arizona.

Faas, S. E. and D. M. McEligot, 1980. Convective heat transfer for ship propulsion. Annual Report, ONR Contract No. N00014 -75-C-0694.

Gosman, A. D. and F. J. K. Ideriah, 1976. TEACH-T: A General Computer program for two-dimensional, turbulent, recirculating flows. Tech. Rpt. (Manuscript), Imperial College.

Habib, M. A. and D. M. McEligot, 1981. Convective heat transfer for ship propulsion. Annual Report, ONR Contract No. N0014 -75-C-0694.

Habib, M. A. and D. M. McEligot, 1982. Turbulent heat transfer in swirl flow downstream of an abrupt pipe expansion. Proc., 7th Intl. Heat Transf. Conf., Munchen.

<u>References Cited</u> (continued)

Krasin, A. K., 1970. Dissociating gases as heat transfer media and working fluids in power installations. AEC-tr-7295, UC-38.

Harrington, R. L., Ed., 1971. <u>Marine Engineering</u>. Revised. New York, N. Y.: Society of Naval Architects and Marine Engineers.

Haynes, G. C., 1970. The dissociating gas power cycle. Proc., A. F. Sci. and Engr. Symposium.

Marto, P. and R. H. Nunn, 1980. Heat transfer in surface condensers. Workshop, USN Postgraduate School, Monterey.

McCullough, J. E., 1985. Convective heat transfer in an asymmetric duct with property variation and surface roughness transitions. M.S.E. Report, Univ. of Arizona, in preparation.

McEligot, D. M., P. E. Pickett and M. F. Taylor, 1976. Measurement of wall region turbulent Prandtl numbers in small tubes. <u>Int. J. Heat Mass Transfer</u>, <u>19</u>, 709- 803.

McEligot, D. M., M. F. Taylor and F. Durst, 1977. Internal forced convection to mixtures of inert gases, <u>Int. J. Heat Mass Transfer</u>, <u>20</u>, 475-486.

McKisson, R. L., 1954. Dissociation-cooling: A discussion. Rpt. LRL-86, U. S. Atomic Energy Commission, Livermore Research Lab.

Park, J. S., M. F. Taylor and D. M. McEligot, 1982. Heat transfer to pulsating, turbulent gas flow. Proc., 7th Intl. Heat Transfer Conf., Munchen.

Park, J. S., M. F. Taylor and D. M. McEligot, 1982. Convective heat transfer for ship propulsion. Annual Report, ONR Contract No. N-00014-FS-C-0694.

Pickett, P. E., M. F. Taylor and D. M. McEligot, 1979. Heated turbulent flow of helium-argon mixtures in tubes, <u>Int. J. Heat Mass Transfer</u>, <u>20</u>, 705-719.

Postan, A., 1982. Preliminary design of dissociating gas power cycles for ship propulsion. Technical report draft (unpublished), Univ. of Arizna.

References Cited (continued)

Pressler, A. F., 1966. An experimental investigation of heat transfer to turbulent flow in smooth tubes for the reacting $N_2O_4 - NO_2$ system. NASA TN D-3230.

Schade, K. W. and D. M. McEligot, 1971. Turbulent flow between plates with gas property variation. ASME paper 71-FE-38.

Serksnis, A. W., M. F. Taylor and D. M. McEligot, 1978. Turbulent flow of hydrogen-carbon dioxide mixtures in heated tubes, Heat Transfer 1978 (Sixth Int. Heat Transfer Conf., Toronto), 2, 163-168.

Shehata, A. M., 1984. Mean turbulence structure in strongly heated air flows. Ph.D. thesis, Univ. of Arizona.

Short, B. E., Jr., 1977. Numerical prediction of heated flow between rib rough surfaces. M.S.E. Report, Aero. Mech. Engr., Univ. of Arizona.

Taylor, M. F., K. E. Bauer and D. M. McEligot, 1984. Internal forced convection to low Prandtl number mixtures. Interim Report, ONR Contract No. N00014-75-C-0694.

Taylor, M. F., K. E. Bauer and D. M. McEligot, 1985. Internal forced convection to mixtures. Int. J. Heat Mass Transfer, accepted for publication.

Zemanick, P. P. and R. S. Dougall, 1970. Local heat transfer downstream of abrupt circular channel expansion, ASME J. Heat Transfer, 92, 53.

INDEX OF TECHNICAL REPORTS

1248-1 McEligot, D. M., M. F. Taylor and P. E. Pickett, 1975. Convection in the closed Brayton cycle, 1st annual summary report.

1248-2 Taylor, M. F., D. M. McEligot and P. E. Pickett, 1975. Deduction of the turbulent Prandtl number in the wall region from wall measurements in the thermal entry.

INDEX OF TECHNICAL REPORTS (continued)

1248-3 Taylor, M. F., P. E. Pickett, F. Durst and D. M. McEligot, 1976. Convection in the closed Brayton cycle, 2nd annual summary report.

1248-4 McEligot, D. M., M. F. Taylor and F. Durst, 1976. Laminar forced convection to mixtures of inert gases in parallel plate ducts. Also tech. rpt. 536, Inst. f. Hydromechanik, Universität Karlsruhe.

1248-5 Pickett, P. E., D. M. McEligot and M. F. Taylor, 1977. Convection in the closed Brayton cycle, 3rd annual summary report.

1248-6 Serksnis, A. W., D. M. McEligot and M. F. Taylor, 1978. Convective heat transfer for ship propulsion, 4th annual summary report.

1248-6a Pickett, P. E., 1978. Heat and momentum transfer to internal turbulent flow of helium-argon mixtures in circular tubes.

1248-7 Faas, S. E. and D. M. McEligot, 1980. Convective heat transfer for ship propulsion, 5th annual summary report.

1248-8 Habib, M. A. and D. M. McEligot, 1981. Convective heat transfer for ship propulsion, 6th annual summary report.

1248-9 Park, J. S., M. F. Taylor and D. M. McEligot, 1982. Convective heat transfer for ship propulsion, 7th annual summary report.

1248-10 Taylor, M. F., K. E. Bauer and D. M. McEligot, 1984. Internal forced convection to low Prandtl number gases.

1248-11 McEligot, D. M., 1985. Convective heat transfer for ship propulsion, final report.

INDEX OF PUBLICATIONS

a. <u>Journals</u>

McEligot, D. M., P. E. Pickett and M. F. Taylor, 1976. Measurement of wall region turbulent Prandtl numbers in small tubes. <u>Int. J. Heat Mass Transfer</u>, <u>19</u>, pp. 799-803.

McEligot, D. M., M. F. Taylor and F. Durst, 1977. Internal forced convection to mixtures of inert gases. <u>Int. J. Heat Mass Transfer</u>, <u>20</u>, pp. 475-486.

Serksnis, A. W., M. F. Taylor and D. M. McEligot, 1978. Turbulent flow of hydrogen-carbon dioxide mixtures in heated tubes. <u>Heat Transfer 1978</u> (Sixth Int. Heat Transfer Conf., Toronto), <u>2</u>, pp. 163-168.

Murphy, H. D., M. Coxon and D. M. McEligot, 1978. Symmetric sink flow between parallel plates.* <u>J. Fluid Engrg.</u>, <u>100</u>, pp. 477-484.

Pickett, P. E., M. F. Taylor and D. M. McEligot, 1979. Heated turbulent flow of helium-argon mixtures in tubes. <u>Int. J. Heat Mass Transfer</u>, <u>22</u>, pp. 705-719.

Park, J. S., M. F. Taylor and D. M. McEligot, 1982. Heat transfer to pulsating turbulent gas flow. Seventh Intl. Heat Transfer Conf., Munchen.

Habib, M. A. and D. M. McEligot, 1982. Turbulent heat transfer in a swirl flow downstream of an abrupt pipe expansion. Seventh Intl. Heat Transfer Conf., Munchen.

McEligot, D. M., S. B. Smith and R. L. Verity, 1982. Wake interference for a heated oscillating cylinder. Seventh Intl. Heat Transfer Conf., Munchen.

Murphy, H. D., F. W. Chambers and D. M. McEligot, 1983. Laterally converging flow. I: Mean flow*. <u>J. Fluid Mech.</u>, <u>127</u>, pp. 379-401.

Chambers, F. W., H. D. Murphy and D. M. McEligot, 1983. Laterally converging flow. II. Temporal wall hear stress.* <u>J. Fluid Mech.</u>, <u>127</u>, pp. 403-428.

---

* Also supported by National Science Foundation.

INDEX OF PUBLICATIONS

a. Journals (continued)

McEligot, D. M., 1984. Heat transfer to gases with varying properties. Adv. Trans. Processes, IV.

McCullough, J. E., M. F. Taylor and D. M. McEligot, 1985. Heat transfer at a smooth-to-rough transition, in preparation.

Taylor, M. F., K. E. Bauer and D. M. McEligot, 1985. Internal forced convection to mixtures. Int. J. Heat Mass Transfer, accepted for publication.

b. Conference Presentations

McEligot, D. M., E. Pils and F. Durst, 1976. Mixed perpendicular convection*, APS Fluid Dynamics Meeting, Eugene (abstract and presentation).

Shehata, A. M. and D. M. McEligot, 1977. Forced convection in simple solar collectors*, Proc. ERDA/FSEC Flat Plate Collector Conference, Orlando.

Snow, R. L. and D. M. McEligot, 1977. Modeling the viscous layer*, APS Fluid Dynamics Meeting, Bethlehem (abstract and presentation).

Shehata, A. M. and D. M. McEligot, 1977. Hot wire anemometry in non-isothermal environments*, APS Fluid Dynamics Meeting (abstract and presentation).

---

* Also supported by National Science Foundation.

INDEX OF PUBLICATIONS

b. Conference Presentations (continued)

Stabile, J. A. and D. M. McEligot, 1978. Effects of heated coherent structures on measurements by laser Doppler anemometry*, Proc. AFOSR Workshop on Coherent Structures of Turbulent Boundary Layers, Lehigh University.

Murphy, H. D. and D. M. McEligot, 1978. Turbulent flow in a spanwise converging duct*, APS Fluid Dynamics Meeting, Los Angeles (abstract and presentation).

McEligot, D. M. and C. A. Bankston, 1979. Forced convection in solar collectors**, Proc. Int. Congr., Int. Solar Energy Soc..

Faas, S. E. and D. M. McEligot, 1979. Flow in a corrugated duct, APS Fluid Dynamics Meeting, Notre Dame (abstract and presentation).

Berner, C. and D. M. McEligot, 1980. Flow around baffles*, APS Fluid Dynamics Meeting, Ithaca.

Chambers, F. W., H. D. Murphy and D. M. McEligot, 1981. Conditional wall shear stress measurements in a rectangular duct*, APS Fluid Dynamics Meeting, Monterey, California.

---

*Also supported by National Science Foundation.

**Also supported by Los Alamos Scientific Laboratory.

DISTRIBUTION LIST -- HEAT TRANSFER

	One copy except as noted
Mr. M. Keith Ellingsworth Materials and Mechanics Program (Code 1132p) Office of Naval Research 800 N. Quincy Street Arlington, VA 22203	5
Defense Documentation Center Building 5, Cameron Station Alexandria, VA 22314	12
Technical Information Division Naval Research Laboratory 4555 Overlook Avenue, S. W. Washington, D. C. 20375	6
Professor Paul Marto Department of Mechanical Engineering U. S. Naval Post Graduate School Monterey, CA 93940	
Professor Bruce Rankin Naval Systems Engineering U. S. Naval Academy Annapolis, MD 21402	
Office of Naval Research Eastern/ Central Regional Office Bldg. 114, Section D 666 Summer Street Boston Massachusetts 02210	
Office of Naval Research Branch Office 536 South Clark Street Chicago, Illinois 60605	
Office of Naval Research Western Regional Office 1030 East Green Street Pasadena, CA 91106	

DISTRIBUTION LIST -- HEAT TRANSFER (continued)

One copy except
as noted

Mr. Charles Miller, Code 05R13
Crystal Plaza #6
Naval Sea Systems Command
Washington, D. C. 20362

Steam Generators Branch, Code 5222
National Center #4
Naval Sea Systems Command
Washington, D. C. 20362

Heat Exchanger Branch, Code 5223
National Center #3
Naval Sea Systems Command
Washington, D. C. 20362

Mr. Ed Ruggiero, NAVSEA 08
National Center #2
Washington, D. C. 20362

Dr. Earl Quandt, Jr., Code 272
David Taylor Ship R&D Center
Annapolis, MD 21402

Mr. Wayne Adamson, Code 2722
David Taylor Ship R&D Center
Annapols, MD 21402

Dr. Win Aung
Chemical Engineering Division
National Science Foundation
1800 G Street, N. W.
Washington, D. C. 20550

Mr. Michael Perlsweig
Department of Energy
Mail Station E-178
Washington, D. C. 20545

Dr. W. H. Thielbahr
Chief, Energy Conservation Branch
Department of Energy, Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

DISTRIBUTION LIST -- HEAT TRANSFER (continued)

One copy except
as noted

Professor E. M. Sparrow
Heat Transfer Program
National Science Foundation
1800 G Street, N. W.
Washington, D. C. 20550

Professor J. A. C. Humphrey
Department of Mechanical Engineering
University of California, Berkeley
Berkeley, California 94720

Professor Brian E. Launder
Thermodynamics and Fluid Mechanics Division
University of Manchester
Institute of Science & Technology
PO88 Sackville Street
Manchester M60 1QD, ENGLAND

Professor Shi-Chun Yao
Department of Mechanical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213

Professor Charles B. Watkins
Chairman, Mechanical Engineering Department
Howard University
Washington, D. C. 20059

Professor Adrian Bejan
Department of Mechanical Engineering
Duke University
Durham, North Carolina 27706

Professor Donald M. McEligot
Gould, Inc.
One Corporate Place
Newport Corporate Park
Middletown, R. I. 02840

DISTRIBUTION LIST -- HEAT TRANSFER (continued))

One copy except
as noted

Professor Paul A. Libby
Department of Applied Mechanics and
Engineering Sciences
University of California, San Diego
Post Office Box 109
La Jolla, CA 92037

Professor C. Forbes Dewey, Jr.
Fluid Mechanics Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Professor William G. Characklis
Department of Civil Engineering and
Engineering Mechanics
Montana State University
Bozeman, Montana 59717

Professor Ralph Webb
Department of Mechanical Engineering
Pennsylvania State University
208 Mechanical Engineering Bldg.
University Park, PA 16802

Professor Warren Rohsenow
Mechanical Engineering Department
Massachusetts Institute of Technology
77 Massachusets Avenue
Cambridge, Massachusetts 02139

Profesor A. Louis London
Mechanical Engineering Department
Bldg. 500, Room 501B
Stanford University
Stanford, CA 94305

Professor James G. Knudsen
Associate Dean, School of Engineering
Oregon State University
219 Covell Hall
Corvallis, Oregon 97331

DISTRIBUTION LIST -- HEAT TRANSFER (continued)

One copy except as noted

Mr. Robert W. Perkins
Turbotec Products, Inc.
533 Downey Drive
New Britain, Connecticut 06051

Dr. Keith E. Starner
York Division, Borg-Warner Corp.
P. O. Box 1592
York, PA 17405

Mr. Peter Wishart
C-E Power Systems
Combustion Engineering, Inc.
Windsor, Connecticut 06095

Mr. Henry W. Braum
Manager, Condenser Engineering Department
Delaval
Front Street
Florence, New Jersey 08518

Dr. Thomas Rabas
Steam Turbine-Generator Technical
Operations Division
Westinghouse Electric Corporation
Lester Branch
P. O. Box 9175 N2
Philadelphia, PA 19113

Dr. Albert D. Wood
Director, Mechanics Program (Code 432)
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22203

Mr. Walter Ritz
Code 033C
Naval Ships Systems Engineering Station
Philadelphia, PA 19112

DISTRIBUTION LIST -- HEAT TRANSFER (continued)

One copy except
as noted

Mr. Richard F. Wyvill
Code 5232
NC #4
Naval Sea Systems Command
Washington, D. C. 20362M

Mr. Doug Marron
Code 5231
NC #4
Naval Sea Systems Command
Washington, D. C. 20362

Professor Arthur E. Bergles
Mechanical Engineering Department
Iowa State University
Ames, Iowa 50011

Professor Kenneth J. Bell
School of Chemical Engineering
Oklahoma State University
Stillwater, Oklahoma 74074

Dr. David M. Eissenberg
Oak Ridge National Laboratory
P. O. Box Y, Bldg. 9204-1, MS-0
Oak Ridge, Tennessee 37830

Dr. Jerry Taborek
Technical Director
Heat Transfer Research Institute
1000 South Fremont Avenue
Alhambra, CA 91802

Dr. Simion Kuo
Chief, Energy Systems
Energy Research Laboratory
United Technology Research Center
East Hartford, Connecticut 06108

DISTRIBUTION LIST -- HEAT TRANSFER (continued)

One copy except
as noted

Mr. Jack Yampolsky
General Atomic Company
P. O. Box 81608
San Diego, CA 92138

Mr. Ted Carnavos
Noranda Metal Industries, Inc.
Prospect Drive
Newtown, Connecticut 06470

Dr. Ramesh K. Shah
Harrison Radiator Division
General Motors Corporation
Lockport, New York 14094

Dr. Ravi K. Sakhuja
Manager, Advanced Programs
Thermo Electron Corporation
101 First Avenue
Waltham, Massachusetts 02154

Mr. T. M. Herder
Bldg. 46462
General Electric Company
1100 Western Avenue
Lynn, MA 01910

Mr. Ed Strain
AiResearch of Arizona
Department 76, Mail Stop 301-2
P. O. Box 5217
Phoenix, AZ 85010

Mr. Norm McIntire
Solar Turbines International
2200 Pacific Highway
San Diego, CA 92101

Professor Darryl E. Metzger, Chairman
Mechanical and Aerospace Engineering Department
Arizona State University
Tempe, AZ 85281

END
FILMED

6-86

DTIC